A New Method to Evaluate, Optimize and Forecast Human and Robot Performance in 21st Century Space Operations

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More In-Depth Quantitative Analysis is Needed to Assess Human-Robot Roles in 21st Century Space Operations

- Relative strengths of humans and robots in performing a wide variety of tasks is well-established CONCEPTUALLY
  - Humans are unequaled in unstructured situations
  - Robots are good at high-risk access
  - Etc.
- There is a wealth of EXPERIENCE to validate these general notions
  - Armstrong's decision-making in lunar terminal descent maneuver could not have been done reliably with robotic spacecraft
  - Robots have gone to "worse-than-hell" places (Venus, Jupiter) not currently accessible to humans
- Systematic comparisons that validate these general concepts have not been fully investigated for a wide range of envisioned surface operations
  - Need standardized METRICS to quantify performance
  - Need rigorously defined criteria to EVALUATE relative performance

Human-Robot Performance Evaluation Process

Scenario

1. Decompose Scenario

Primitives: Discover rocks, Carry rocks, Traverse, Recover from mishaps, etc.

2. Quantify Primitive Parameters

Parameters: EVA duration, traverse distance, rock abundance, etc.

3. Determine Aptitudes

Scores / primitive for each HR system option: data base, thought experiments; consensus models; etc.

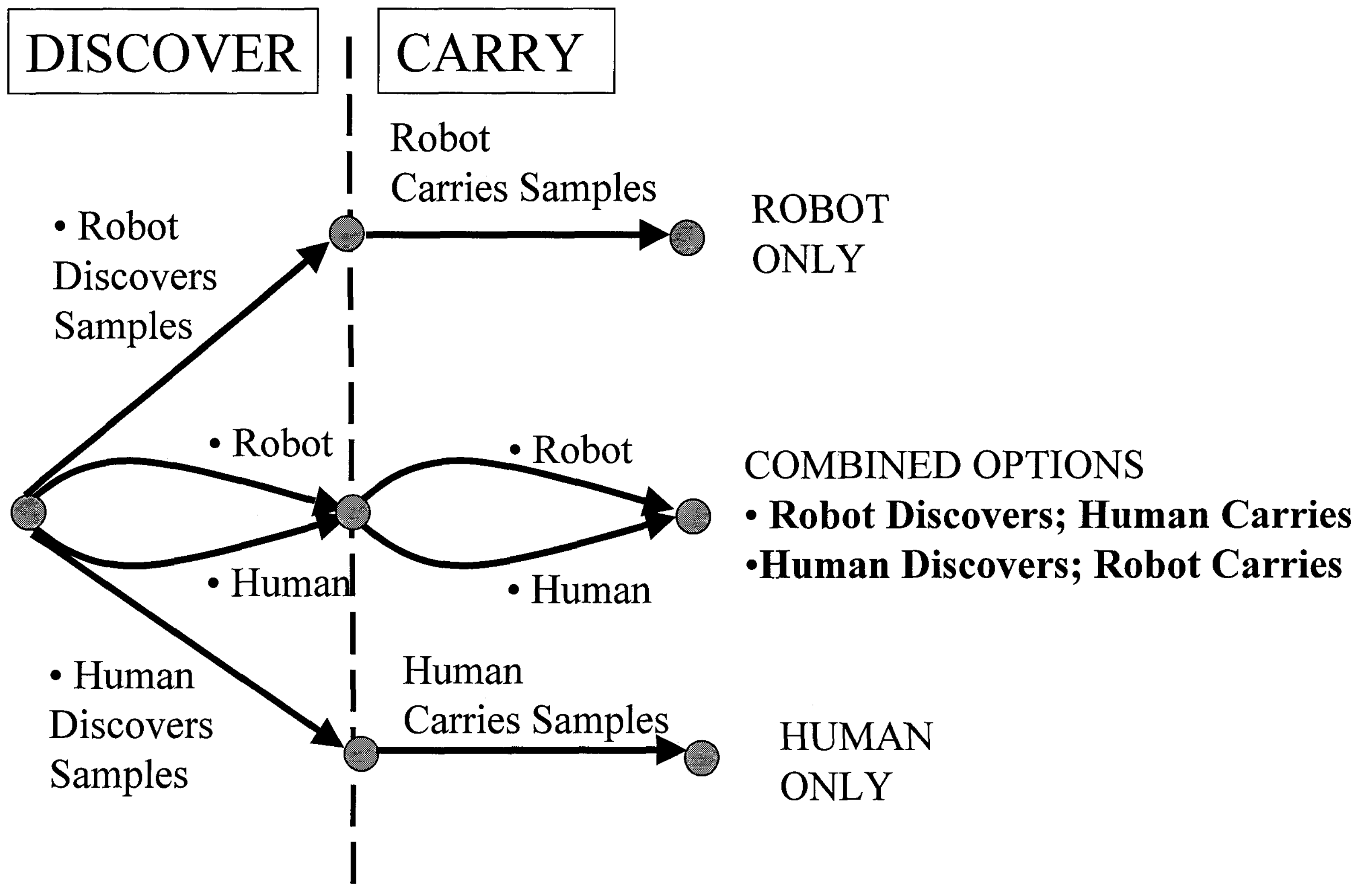
4. Compute Composite Scores

Multi-primitive scores: e. g., probability of success

Human-Robot (HR) System Options

- 2 Astronauts walk
- 2 Rover scouts
- 2 Astronauts ride transport vehicle
- Robot assists 2 walking astronauts
- 2 Autonomous rovers controlled from Earth
  - State-of-art autonomy: 1 command load for each sol
  - Projected autonomy: 1 command load for multiple sols

Example: 4 Ways to Do Sequence of 2 Primitives



Aptitude Scoring Table

Performance, Resources & Value-Added

PRIMITIVES	Human	Log	Robot	Log	Human &	Log
	Only	Ratio	Only	Ratio	Robot	Ratio
Discover Samples	8.0	0.0	2.0	-2.0	9.0	0.2
Carry Samples	3.0	0.0	7.0	1.2	8.0	1.4
Relative Performance (bits)		0.0		-0.8		1.6
RESOURCE DEMAND						
System Mass (kg)	140.0	0.0	50.0	-1.5	190.0	0.4
Power (kW)	0.5	0.0	1.0	1.0	1.5	1.6
Relative Resources (bits)		0.0		-0.5		2.0
Relative Value Added (bits)		0.0		-0.3		-0.4

- Log Ratio = Log_2(Agent Score/Reference Score)
- Human-only score is used as reference in the table
- Other references can be used (robot only; human & robot; requirements; etc.)
- Relative Value = Log Ratio(performance) - Log Ratio (Resources)
- Use of Log Ratios simplifies book-keeping among many other benefits

Field Geology and Sample Collection Scenario
--Discover & Collect Sedimentary Rocks--

- Single EVA Primitives & Requirements
  - Traverse – max. safe range; rough, unexplored terrain
  - Discover rocks - sedimentary; low % abundance
  - Carry rocks - mixed collection & sedimentary
  - Recover from mishaps - likelihood of safe return
  - Be there - EVA duration
- Other Important Mission Primitives
  - Process rock samples
  - Analyze in-situ & prepare for return to Earth
  - Deploy special payloads
    - •ISRU oxygen generator
    - •Habitat infrastructure (re-visitable)
    - •Power generator & deep drill

Gullies of Mars Valles Marineris. Original image from NASA/JPL/Malin Space Science Systems

•*Derived from Section 2.3, Page 21, "The Mars Surface Reference Mission," S. J. Hoffman, Ed., Oct. 1998.

A Brief Description of Each Phase in Evaluation Process

--Applied to Field Geology & Sample Collection Scenario--

1. Decompose Scenario • **Identify Major Functions:** Discover & Identify Rocks; Carry Rocks, Traverse, Recover from Mishaps • **Organize by Scale & Resolution:** Astronomical; Planet Globe; Regional; Local Site; System; Sub-System; Components; etc. • **Down-Select to Primitives to be Used for System Evaluation**	• 2. Quantify Primitive Parameters • **Find & Identify Rocks:** % Rock Abundance; Single Trial Probability of Success; Sampling Rate; Rock Sampling Time; Expected # of Rock Finds; Effective Traverse Rate • **Carry Rocks:** Total Rock Mass & Volume; Loaded Traverse Rate; Traverse Time; Distance • **Recover from Mishaps:** Single Mishap Probability of Recovery; Expected Number of Mishaps; Probability of Safe Return
3. Determine HR System Aptitudes • **Identify HR System Options & Resources:** human only; robot only; combined human-robot; etc. • **Evaluate HR System Performance:** thought experiments; models; data bases; analysis • **Quantify HR System Option Resource Demands:** mass; power; volume; risk margins;etc. • **Determine Aptitude Scores for Each Primitive and HR System Option**	4. Compute Composite Scores • **Design Multi-Primitive Tree:** Each tree branch represents a primitive score • **Compute Composite System Resources:** total mass; power, volume, etc. • **Compute Composite Tree Scores:** total performance metrics, e.g., probability of success • **Compute Value-Added:** relative performance - relative resources with respect to selected reference

Main Issues in Field Geology & Sample Collection

How to get best performance

- Compare levels of performance that can be achieved by various candidate human-robot surface system configuration options
    - 2 EVA Astronauts Walk
    - 2 Rover Scouts
    - 2 EVA Astronauts Ride Rover
    - Robot Assists 2 Walking EVA Astronauts
    - 2 Autonomous Robots Controlled from Earth

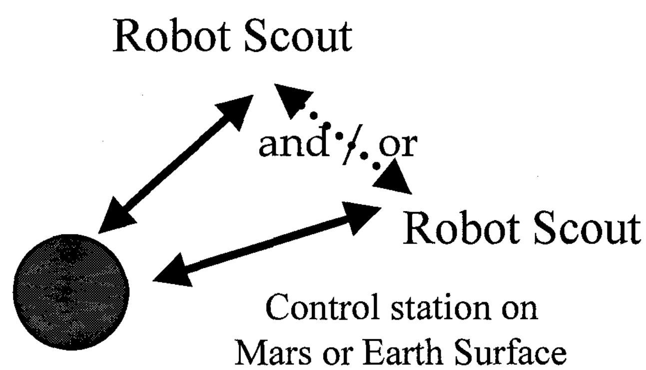
Given that safety is a primary concern

- "Crew safety concerns when entering a region highly dissimilar from any explored before or an area with a high potential for biological activity may dictate the use of a rover in advance of the crew."

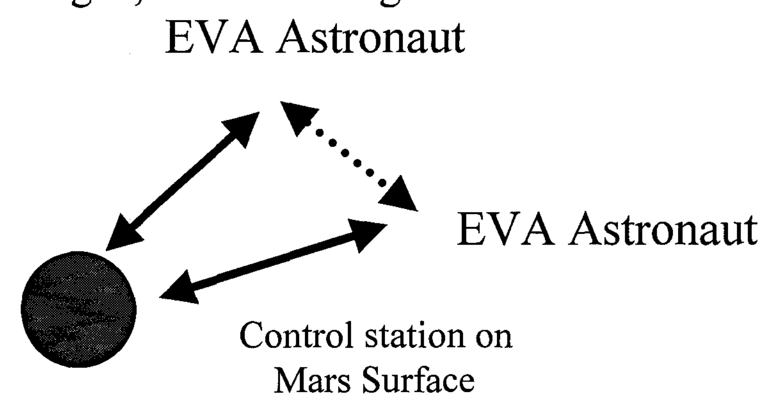
[Exploration Field Work, Section 2.3, Page 21, Mars Surface Reference Mission: A Description of Human Robotic Activities, edited by S. J. Hoffman, Oct., 1998]

Illustration of Human-Robot Surface System Options

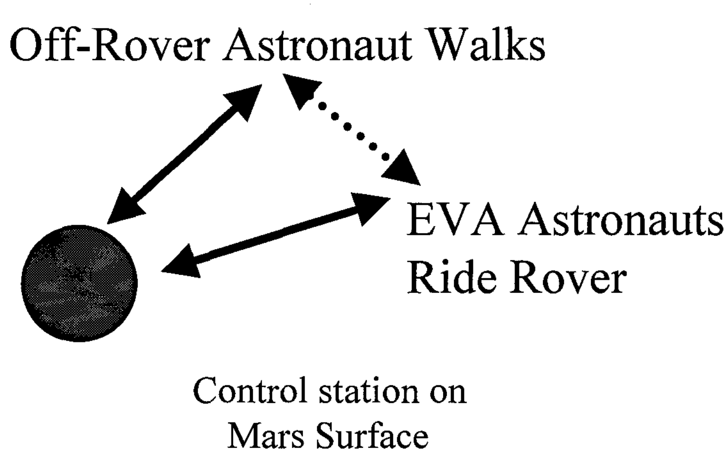
Rover Scouts: low mass; speed; extended range; tele-present geologist



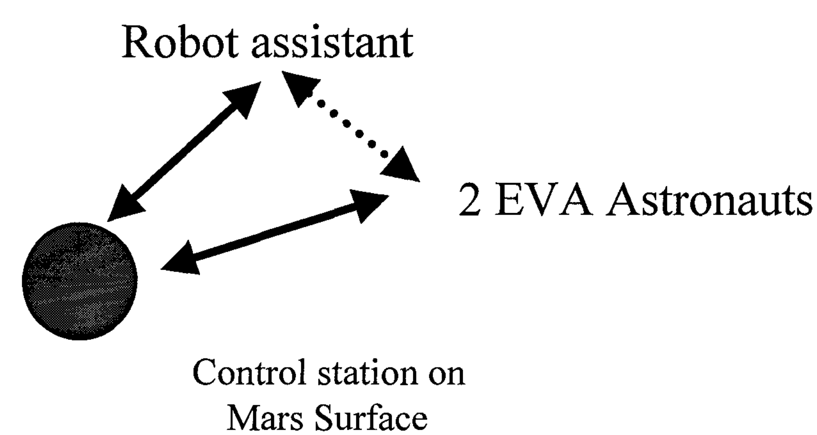
2 EVA Astronauts Walk: in-situ expert geologist; moderate range



2 EVA Astronauts Ride Rover

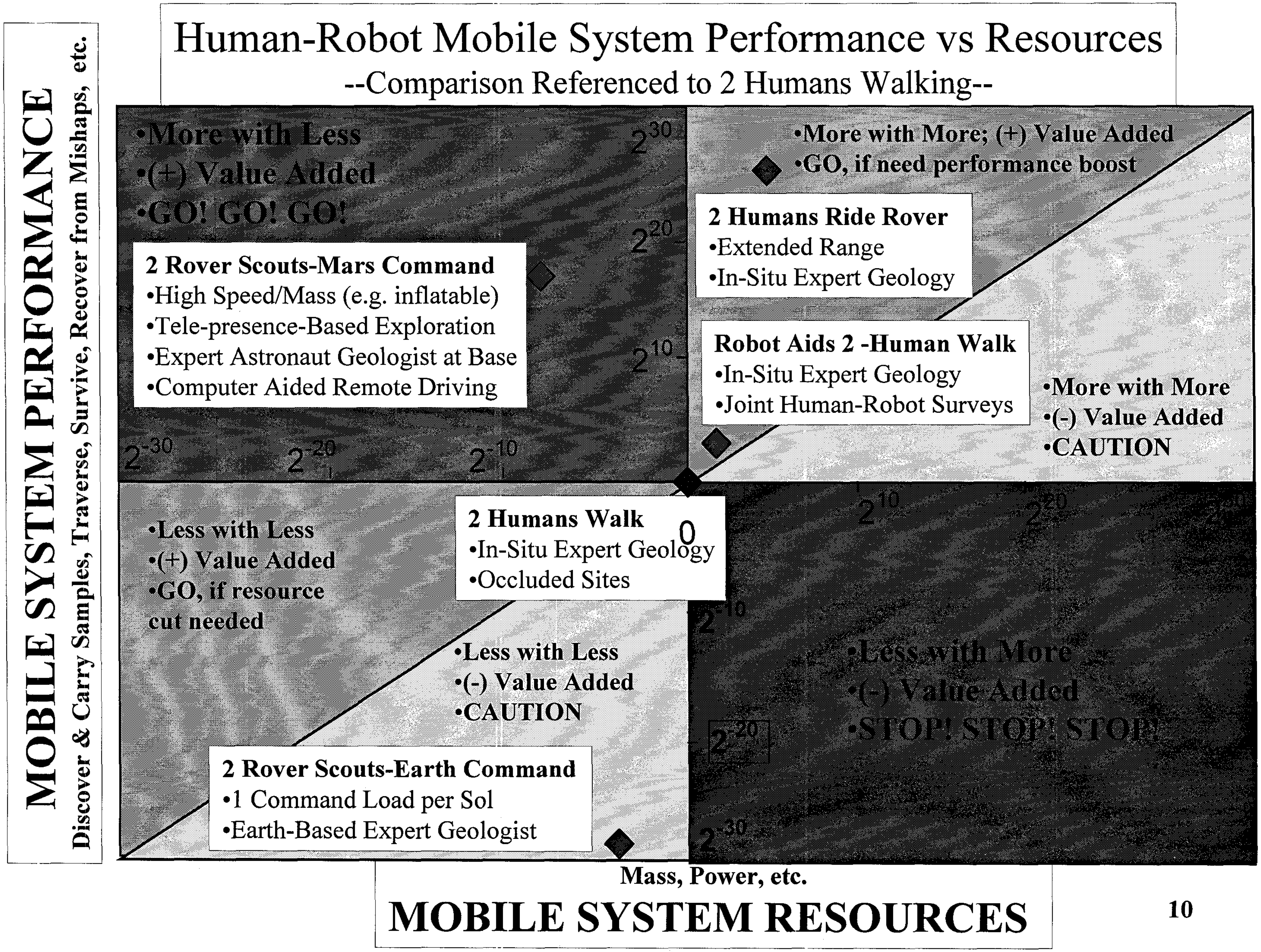


Rover-Assists 2 Astronauts: joint surveys; load sharing

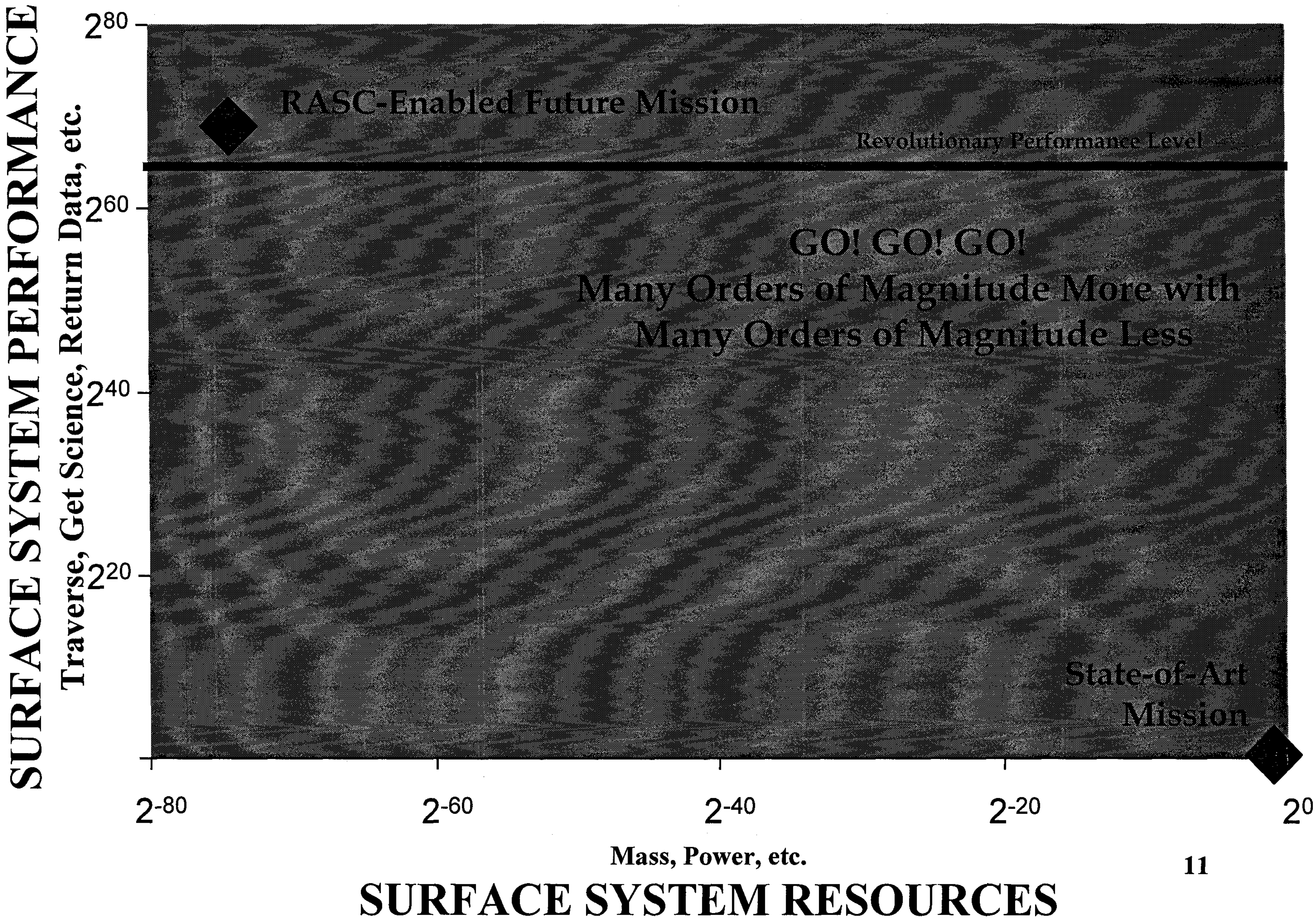


Qualitative Assessment of 5 System Options

Human-Robot Surface System Options	Performance of System Options	Mobile Resources Required
2 EVA Astronauts Walk	**Limited Range; at-the-site expert geology**	**Moderate mass; power**
2 EVA Astronauts Ride Rover	**Extended range; at-the-site expert geology**	**Higher mass; power**
2 Rover Scouts Controlled from Mars Base	**Expert geology tele-presence; extended range**	**Low mass; low power**
Robot Assists 2 EVA Astronauts	**Coordinate area coverage; load carry aid**	**Moderate-Plus mass; power**
2 Robots Controlled from Earth	**Low effective traverse rate; high autonomy**	**Lowest mass & power**


Human-Robot Mobile System Performance vs Resources
--Comparison Referenced to 2 Humans Walking--
MOBILE SYSTEM PERFORMANCE
Discover & Carry Samples, Traverse, Survive, Recover from Mishaps, etc.
•More with Less
•(+) Value Added
•GO! GO! GO!
2 Rover Scouts-Mars Command
•High Speed/Mass (e.g. inflatable)
•Tele-presence-Based Exploration
•Expert Astronaut Geologist at Base
•Computer Aided Remote Driving
•More with More; (+) Value Added
•GO, if need performance boost
2 Humans Ride Rover
•Extended Range
•In-Situ Expert Geology
Robot Aids 2 -Human Walk
•In-Situ Expert Geology
•Joint Human-Robot Surveys
•More with More
•(-) Value Added
•CAUTION
2^{30}
2^{20}
2^{10}
2^{-30}
2^{-20}
2^{-10}
0
2^{10}
2^{20}
2^{-10}
2^{-20}
2^{-30}
•Less with Less
•(+) Value Added
•GO, if resource cut needed
2 Humans Walk
•In-Situ Expert Geology
•Occluded Sites
•Less with Less
•(-) Value Added
•CAUTION
•Less with More
•(-) Value Added
•STOP! STOP! STOP!
2 Rover Scouts-Earth Command
•1 Command Load per Sol
•Earth-Based Expert Geologist
Mass, Power, etc.
MOBILE SYSTEM RESOURCES

Forecast for RASC-Enabled Future Missions



Revolutionary SUPER-HUMAN Skills

Functions	In-Space SOA Performance	Revolutionary Performance
BREATHE	Heavy Back-Pack	Miniaturized ISRU Unit
WALK	Suit-Impaired	Suit-Augmented
TALK	Discrete/Selected Sites	Distributed/Selectable; wide-bandwidth
GRASP	Glove Impaired	Glove Augmented
HOP	Short range; unsafe	Long range; safe
TOUCH	Glove Impaired	Glove Augmented
SEE	Daylight; headgear impaired	Day/Night; Multi-Spectral; Zoom In/Out
THINK	Supreme	Supreme-Plus-Plus
THROW	Suit Impaired	Suit Augmented
OTHER	Limited by Human Physiology & Suit	Expands Range of Natural Human Skills

Revolutionary SUPER-ROBOT Skills

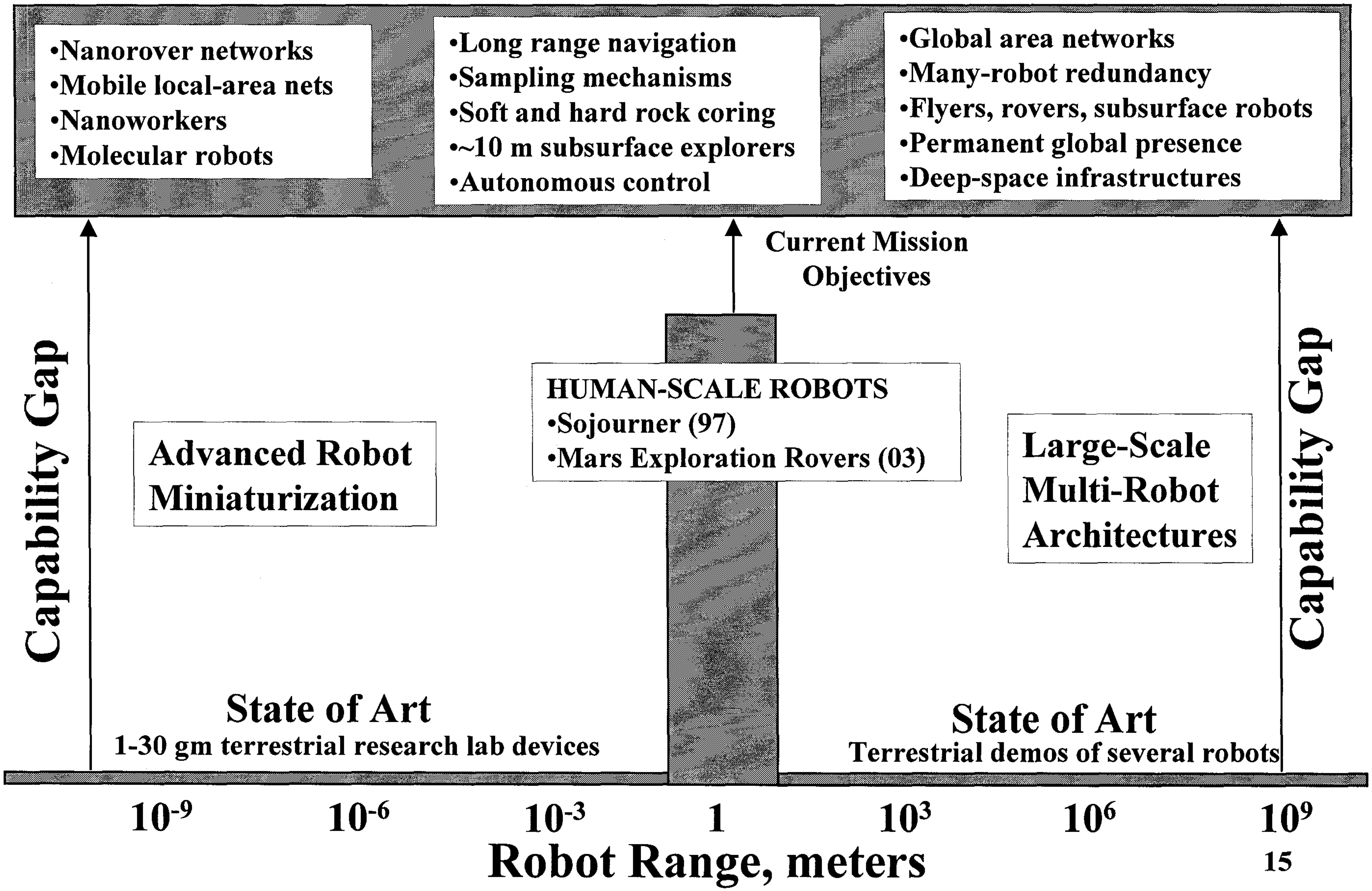
Functions	In-Space SOA Performance	Revolutionary Performance
SURVIVE	Solar Power	Live-off-Land
TRAVERSE	Benign Terrain	High-Risk Terrain
COMMUNICATE	Discrete/Selected Sites	Distributed/Selectable; wide-bandwidth
GRASP	Few DOF; small force	Many DOF; large force
HOP	Limited Range; unsafe	Unlimited Range; Safe
TOUCH	Point Sensors	Distributed Skins
SEE	Daylight; headgear impaired	Day/Night; Multi-Spectral; Zoom In/Out
THINK	Moderate	Supreme
LIFT	Low-g Heavy	High-g Heavy
WORK	Focused on Human-Scale Robot; some R & D on miniaturization	Expands Range in size, perception, cognitive and motor skills

SUPER HUMAN+ROBOT ARCHITECTURES

(One Plus One = 999 Billion)

Functions	In-Space SOA Performance	Revolutionary Performance
EXPLORE	Remote Robot Controlled from Earth or LEO	1 Controller Commands Many Robots at Once
MANIPULATE	SRMS & ISS RMS	1 Controller Commands Robot Work Crew
ACCESS	10s of Meters	Multi-Scale; from Nano-to-Macro Scales
WORK	Servicing & Assembly in LEO	Heavy-Duty Assembly; Excavation; Terraform
INTERACT (Human & Robot)	Limited-Autonomy; teleoperation	Minimalist; highest-level commands
COOPERATE	Robot Manipulator Assists Astronauts	Cooperative Human-Robot Teams (beyond LEO)

Future Human-Robot Architectures
(Plenty of Room at the Bottom & Top)



Concluding Remarks

- It is possible to conduct QUANTITATIVE ASSESSMENTS of human, robot, and hybrid human-robot systems
    - Organize very difficult set of issues into a methodical framework
    - Produce results that are easy to interpret and understand
    - Provide comparisons that can be verified, or changed rationally if needed
    - Many different data types (numerical, logical, probabilities, etc.)
- A STANDARD REFERENCE can be selected and CHANGED easily by the user of the method.
    - HUMAN-CENTERED or ROBOT-CENTERED
    - OPTION X-CENTERED (Selectable by User)
- Value of being able to go back-and-forth from Human-Centered to Robot-Centered and to any designated point of view
    - Tools for impartial, analytical discussion of human-robot roles
    - Comparisons that can be free of bias and pre-conceived notions
- Additional case studies will extend applicability of the method, e.g.,
    - DISCOVER primitive (Serendipity-Based)
    - Super-Human-Robot Architectures
    - Humans Beyond Mars